

Young Globular Clusters and Dwarf Spheroidals

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ABSTRACT

Most of the globular clusters in the main body of the Galactic halo were formed almost simultaneously. However, globular cluster formation in dwarf spheroidal galaxies appears to have extended over a significant fraction of a Hubble time. This suggests that the factors which suppressed late-time formation of globulars in the main body of the Galactic halo were not operative in dwarf spheroidal galaxies. Possibly the presence of significant numbers of “young” globulars at $R_{GC} > 15$ kpc can be accounted for by the assumption that many of these objects were formed in Sagittarius-like (but not Fornax-like) dwarf spheroidal galaxies, that were subsequently destroyed by Galactic tidal forces. It would be of interest to search for low-luminosity remnants of parental dwarf spheroidals around the “young” globulars Eridanus, Palomar 1, 3, 14, and Terzan 7. Furthermore multi-color photometry could be used to search for the remnants of the super-associations, within which outer halo globular clusters originally formed. Such envelopes are expected to have been tidally stripped from globulars in the inner halo.

Subject headings: Globular clusters - galaxies: dwarf

The galaxy is, in fact, nothing but a
congeries of innumerable stars grouped
together in clusters.
Galileo (1610)

1. Introduction

The vast majority of Galactic globular clusters appear to have formed at about the same time (e.g. Richer et al. 1996, Sarajedini, Chaboyer & Demarque 1997, Stetson, VandenBerg, & Bolte 1996). For various caveats that apply to the age determinations of globular clusters the reader is referred to VandenBerg (1999). Even the outer halo globular cluster NGC 2419 (Harris et al. 1997), located at a Galactocentric distance of ~ 0.10 Mpc, and the majority of the globulars in the Fornax dwarf at $R_{GC} = 0.14$ Mpc (Buonanno et al. 1998), have approximately the same age as the bulk of the globulars in the main body of the Galactic halo. Similar ages are also found for the globular clusters associated with the Large Magellanic Cloud (Olsen et al. 1998, Johnson et al. 1998).

However, a few globular clusters appear to have significantly smaller ages. Presently known (or suspected) “young” globulars are: Palomar 12 (Stetson et al. 1989, Rosenberg et al. 1998b), Ruprecht 106 (Buonanno et al. 1993), IC 4499 (Ferraro et al. 1995), Rup 106, Arp 2, Pal 12 and Terzan 7 (Richer et al. 1996), Pal 12, Terzan 7, Rup 106, Arp 2 (Fusi Pecci et al. 1995), Arp 2 and Terzan 7 (Montegriffo et al. 1998), Pal 1, Pal 3, Pal 4, and Eridanus (Stetson et al. 1999), Fornax No. 4 (Marconi et al. 1999), Palomar 14 (Sarajedini 1997), and perhaps NGC 4590 (= M 68). The latter cluster was regarded as “young” by Chaboyer et al. (1996), but was considered to be of average age by Richer et al. (1996). Table 1 gives a compilation of data on the globular clusters that have been listed as being young. It should be emphasized that the calculated age differences between “young” clusters, and more typical Galactic globular clusters, might be reduced if $[\alpha/\text{Fe}]$ is smaller than was assumed. Available data suggest (Sarajedini 1999) that the age range of globular clusters increases with metallicity from perhaps 1.5 Gyr to 2 Gyr at $[\text{Fe}/\text{H}] \sim -1.6$, to 2–3 Gyr at $[\text{Fe}/\text{H}] \sim -1.0$.

It is presently not clear if the cluster Pal 1 (Rosenberg et al. 1998a, c) at $R_{GC} = 11.7$ kpc, $Z = +3.7$ kpc, with $[\text{Fe}/\text{H}] = -0.8$, $M_V = -2.5$, and an age of ~ 7 Gyr is, in fact, an open or a globular cluster. Perhaps it represents a transitional type of object. Because of its small radius and low population the evaporation time-scale for Pal 1 is only ~ 0.7 Gyr (Rosenberg et al. 1998a). A large initial population of such low-mass clusters might have become extinct. Another object that could be intermediate between open and globular clusters is Lyngå 7 (Ortolani, Bica & Barbuy 1993, Tavaréz & Friel 1995). The observation that the very luminous outer halo globular cluster NGC 2419 is old (Harris et al. 1997), whereas younger outer halo globulars, such as Pal 3, Pal 4 and Eridanus, are relatively young (Stetson et al. 1999), suggests the possibility that the mean luminosity (mass) with which globular clusters formed in the outer halo might have decreased with time, from values that are characteristic of typical globulars, to values that are more similar

to those of the typical open clusters which are still being formed in the Galactic disk at the present time. A possible argument against this idea is that there seems to be no obvious correlation between the ages and the luminosities of the globular clusters in Sagittarius (Montegriffo et al. 1998) and Fornax (Marconi et al. 1999). Such a correlation might have been expected if the globulars in the outer halo had been formed in dwarf spheroidals which were subsequently disrupted. It is presently not entirely clear why there was a guillotine-like cut-off in the rate of globular cluster formation in the inner Galactic halo, while observations of Ter 7 suggest that such cluster formation continued for up to ~ 7 Gyr in dwarf spheroidals. Possibly Searle-Zinn (1978) fragments, with orbits that took them to $R_{GC} < 15$ kpc, were tidally destroyed or stripped of gas on a relatively short time-scale. Some of these ideas have previously been discussed by Freeman (1990) and by Bassino, Muzzio & Rabolli (1994).

A listing of data on presently known “young” globular clusters, based mainly on Harris (1996), which was supplemented by data listed 1999 June 22 at <http://physun.physics.mcmaster.ca/Globular.html>, is given in Table 1. With the exception of NGC 4590 at $R_{GC} = 10.0$ kpc (which is not “young” according to Richer et al.) all of these globulars are located in the outer halo at $R_{GC} > 15.0$ kpc. Many of these clusters are seen to have below-average luminosities (van den Bergh 1998). Eleven of the 40 globulars situated at $R_{GC} > 15.0$ kpc are presently known to be “young”. The true fraction of such objects of below-average age in the outer halo is probably even greater. This is so because high-quality color-magnitude diagrams, that reach down below the main sequence turnoff, are not yet available for quite a few of the distant clusters in the outer halo of the Milky Way system.

2. Globulars in Dwarf Spheroidals

From the updated compilation of Harris (1996) it is found that the Galactic halo contains 31 globular clusters with $R_{GC} > 15.0$ kpc. Furthermore there are four globulars associated with the Sagittarius dwarf spheroidal galaxy (Ibata, Gilmore & Irwin 1994) at $R_{GC} = 18.6$. A fifth (Palomar 12) has both a velocity, and a position on the sky, which suggests that it was originally associated with, and subsequently stripped from, the Sagittarius dwarf (Irwin 1999). An additional five globular clusters are situated in the Fornax dwarf spheroidal galaxy at $R_{GC} = 0.14$ Mpc. The total cluster population (excluding globulars associated with the LMC and SMC) beyond 15 kpc is therefore 40. Table 1 shows that 11 of these objects, i.e. a quarter of the total, are now thought to be “young”. Within Fornax one (Fornax No. 4) out of five

clusters is “young” (Marconi et al. 1999). In Sagittarius two out of four (or three out of five if Pal 12 is included) are “young”. These numbers are consistent with the notion that all globular clusters, that are presently located in the outer halo of the Galaxy, might originally have formed in dwarf spheroidals (most of which subsequently suffered destruction by Galactic tides). Alternatively Lee & Richer (1992) proposed that young clusters, such as Pal 12 and Rup 106, might have been tidally captured from the Magellanic Clouds. However, the metallicity of these clusters appears too low to be consistent with this hypothesis. Pal. 12 has $[\text{Fe}/\text{H}] = -1.0$ and Rup. 106 has $[\text{Fe}/\text{H}] = -1.45$ (Brown, Wallerstein & Zucker 1997). Both of these values are lower than those presently prevailing in the Clouds of Magellan. They would therefore have to have been formed long ago, before the LMC and SMC were enriched significantly in heavy elements. However, (admittedly uncertain) orbital simulations by Byrd et al. (1994) suggest that the Magellanic Clouds were still located near $M 31 \sim 10$ Gyr ago, and were not captured by the Galaxy until ~ 6 Gyr ago. Furthermore, any physical association between Pal 12 and the Magellanic Clouds would conflict with Irwin’s (1999) suggestion that this object was, in fact, stripped from the Sagittarius dwarf spheroidal galaxy. The Sagittarius dwarf might originally have been a Searle-Zinn fragment (Searle & Zinn 1978), which formed in the outer Galactic halo, and that was subsequently scattered into a shorter period orbit by gravitational interaction with the Magellanic Clouds (Zhao 1998, van den Bergh 1998). However, an argument against this hypothesis (Jiang & Binney 1999) is that the velocity of encounter between the Clouds and the Sagittarius dwarf may have been too large for the Magellanic Clouds to deflect it through a significant angle.

Inspection of Table 1 shows that three out of 11 (27%), or four out of 11 (36%) if Pal 12 is included, of all “young” globulars are associated with known dwarf spheroidal galaxies. This suggests that it might be worthwhile to use the digitized version of the Second Palomar Sky Survey to search for additional very faint (and so far undiscovered) dwarf spheroidals surrounding the other “young” globulars listed in Table 1. Such a search would, however, be quite difficult because the postulated faint spheroidals associated with “young” globulars are relatively nearby, and are therefore expected to subtend a large angle on the sky. In view of this problem it might turn out to be more efficient to use multi-color photometry of large fields surrounding each “young” globular to search for these hypothetical parental objects.

Ambartsumian (1955) wrote “It seems probable that the development of an association involves both expansion and the formation of one or more open clusters.” He cited the example of the cluster IC 348 in the association Per OB2. Perhaps the best known case of clusters in an association is the (positive energy) association Per OB1 within which are located the two (negative energy)

clusters h Per (NGC 869) and χ Per (NGC 884). [For a complete listing of clusters associated with associations the reader is referred to the compilation by Ruprecht (1966).] The existence of stable clusters within associations suggests that globular clusters may, at the time of their formation, also have been embedded in massive associations. Parts of such associations might have survived at large Galactocentric distances. However, most of the associations surrounding globulars in the inner part of the Milky Way system would probably have been dispersed long ago by Galactic tidal forces. It should be noted that such globulars in the main body of the halo are expected to be surrounded by tidal debris consisting of material detached from the clusters themselves (Grillmair 1998). From an observational point of view it will be difficult to distinguish between the remnant of a primordial association and tidally stripped material of similar age and chemical composition. Since tidal forces in the Magellanic Clouds will generally be lower than they are in the Galaxy, it might be easier to find ancestral super-associations around the outer globular clusters of the LMC, than it would be to find traces of such structures near Galactic globulars. Binary and multiple clusters [see Pietrzyński and Udalski (1999) for a review] in the SMC might be tracers of such large old associations. Bica et al. (1998) have observed the unique old Large Cloud cluster ESC 121-SC02, which has an age of ~ 9 Gyr, to be embedded in a field population of similar age. Since ESO 121-SC02 is located in the outer reaches of the LMC it is possible that these stars are the remnants of the association within which this cluster formed. In this connection it is of interest to note (Schweizer 1999) that the young knot S, in the merging galaxy NGC 4038, has a cluster-like core with $M_V = -16$, that is embedded in a power-law like envelope containing hundreds of stars out to a distance ~ 450 pc. This may represent an example of a “young globular cluster” that is still embedded in its ancestral super association.

3. Globular Cluster Radii

Figure 1 shows a plot (based on an update of the data in Harris 1996) of the half-light radii R_h of globular clusters as a function of their Galactocentric distances R_{GC} . For isolated clusters such half-light radii are valuable diagnostic tools because they remain almost independent of cluster evolution over ~ 10 cluster relaxation times (Spitzer & Thuan 1972, Hénon 1973, Lightman & Shapiro 1978, Murphy, Cohn & Hut 1990). The data plotted in Figure 1 show that globular clusters situated in the outer halo are systematically larger than those located closer to the Galactic center. That this relationship is not entirely due to the tidal destruction of large globular clusters at small values of R_{GC} is demonstrated by the fact that no small compact clusters occur at large values of R_{GC} , even though such compact objects would easily have survived the weak tidal field in the outer halo. Van den

Bergh (1995) showed that an even tighter relationship exists between the sizes of Galactic globulars and their perigalactic distances. A similar relationship between half-light radii and galactocentric distances is observed for both open clusters, and globular clusters, in the Large Magellanic Cloud (LMC) (van den Bergh 1994).

Inspection of Figure 1 shows that the distribution of “young” globular clusters, and of the globular clusters associated with the Sagittarius system, does not differ from that of Galactic globulars. However, the globular clusters in the Fornax dwarf are located well to the right of the distribution for globulars associated with the Galaxy. This result suggests (not surprisingly) that the Fornax system, at a distance of 0.14 Mpc, developed independently, and was never part of the Milky Way protogalaxy. Figure 2, which is based on the data in Table 2 of van den Bergh (1984), shows that the globular clusters in the Large Magellanic Cloud exhibit a close relationship between galactocentric distance and half-light radius R_h . This shows that the LMC cluster system developed independently from the Galactic globular cluster system. Intercomparison of Figure 1 and Figure 2 shows that the Large Cloud globulars are, at a given galactocentric distance, systematically larger than most of their Galactic counterparts.

4. Chemical Signature of Slow Evolution

Brown, Wallerstein & Zucker (1997) have made spectroscopic abundance determinations for a few stars in the “young” globular clusters Rup 106 and Pal 12. They find that the abundance ratios in these clusters are peculiar. Brown et al. note that the ratios of α -elements [defined as the even-even nuclei from Mg to Ti] to iron are not enhanced over their solar ratios, as they are in most globular clusters and metal-poor halo stars. The most straightforward explanation for this is that the stars in Rup 106 and Pal 12 were formed from gas which had been enriched in iron on a slow time-scale by supernovae of Type Ia. For Rup 106 Brown et al. find $[\text{Fe}/\text{H}] = -1.45 \pm 0.10$ and $[\text{O}/\text{Fe}] = 0.0 \pm 0.1$. Only a small number of high-velocity stars are presently known to exhibit such a low $[\alpha/\text{Fe}]$ abundance. Nissen & Schuster (1997) find that the smallest values of $[\alpha/\text{Fe}]$ occur for those halo stars that have the largest values of $R(\text{apo})$ and the greatest distances from the Galactic plane. However, this conclusion is not confirmed by Stephens (1999). The reason for this disagreement is not yet understood, but might be related to sample selection. The stars in the sample of Nissen & Schuster were biased towards objects with low orbital velocities, and therefore have $R(\text{peri}) < 1.0$ kpc, whereas the stars in Stephens’ sample were selected to have large $R(\text{apo})$. All but one of the members of the Stephens’ sample have

$R(\text{apo}) > 25$ kpc. Gilmore & Wise (1998) point out that tidal capture of a low-density dwarf galaxy will result in its disruption. As a result it is highly unlikely that stars from such a dwarf will sink to very small $R(\text{peri})$ distances.

Both theory (Leonard & Duncan 1990) and observation (Blaauw 1961, Gies & Bolton 1986) lead one to expect that binaries will be rare (or absent) among stars that have undergone a significant amount of dynamical acceleration. Binary/multiple stars that have very high space velocities are therefore likely to be true halo stars that were formed during the first violent (most chaotic) phase of Galactic evolution. One of the few presently known examples of such a high velocity binaries is HD 134439/40 (King 1997). The (retrograde) space velocity of these objects is 565 km s^{-1} , and their metallicity is $[\text{Fe}/\text{H}] \sim -1.5$. King notes that $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, and $[\text{Ca}/\text{Fe}]$ in HD 134439/40 are consistently ~ 0.3 dex lower than they are in the vast majority of metal-poor stars in the Galactic halo. According to Carney et al. (1994) HD 134439/40 have plunging orbits with $R(\text{apo}) = 43$ kpc and $R(\text{peri}) = 4$ kpc, which suggests that they were formed in the outer halo, or that they were captured rather late in the evolutionary history of the protoGalaxy.

Another (rare) example of an α -deficient high velocity star is the subgiant BD +80° 245, which has $[\alpha/\text{Fe}] = -0.29 \pm 0.02$ (Carney et al. 1997). According to Carney et al. this object is on a plunging orbit with $R(\text{apo}) = 22$ kpc. Other stars with low $[\alpha/\text{Fe}]$ are HD 6755 and HD 108577 (Carney 1999). It should, however, be emphasized that not all α -poor high-velocity stars are halo objects. King (1997) has, for example, drawn attention to the star BD +3° 740, with $[\text{Fe}/\text{H}] \sim -3$, in which $[\text{Mg}/\text{Fe}]$ and $[\text{O}/\text{Fe}]$ are ~ 0.5 dex lower than in most metal-poor field stars (Fuhrmann, Axer & Gehren 1995). This object, which has $R(\text{apo}) = 10$ kpc and $R(\text{peri}) = 2$ kpc (Carney et al. 1994), is clearly not a member of the outer halo population of the Galaxy. The fact that the α -elements in the aforementioned objects are only about half as abundant, relative to iron, as they are in the overwhelming majority of metal-poor stars indicates that they were formed in an environment in which fast enrichment of α -elements by SNe II was relatively less important than the slower enrichment of Fe produced by SNe of Type Ia. Alternatively, one can make the ad hoc assumption that the environment in which these stars were produced did not favor the formation of the massive stars that are the progenitors of α -element producing supernovae of Type II. Browne et al. suggest that the apparent deficiency of s-process elements that is observed in Rup 106 might be due to the fact that such “young” globulars formed after SNe Ia had contributed most of their iron, but before the s-process contributors had evolved and shed their outer layers.

It is noted in passing that the value $[\text{Fe}/\text{H}] \sim -1.5$ that King (1997) obtain for HD 134439/40 is indistinguishable from $\langle [\text{Fe}/\text{H}] \rangle = -1.49 \pm 0.11$ that Rodgers & Paltoglou

(1984) found for the seven Galactic globulars that are known to be in retrograde motion. The old globular cluster NGC 3201, which is in a retrograde orbit and has $[\text{Fe}/\text{H}] = -1.42 \pm 0.3$, exhibits the usual excess of α -elements (Gonzalez & Wallerstein 1998). This observation supports the hypothesis that $[\alpha/\text{Fe}]$ for metal-poor objects is mostly determined by their ages, rather than by their orbital characteristics. It is, however, puzzling (Wallerstein, Brown, & Gonzalez 1998) that two stars in M 54 (= NGC 6715), which is located in the Sagittarius dwarf, appear to be slightly oxygen deficient having $[\text{O}/\text{Fe}]$ values of -0.23 ± 0.16 and -0.10 ± 0.17 , respectively. This is so even though M 54 appears to be approximately the same age ($\Delta T = +1.0 \pm 2.0$ Gyr) as the old globular cluster Ter 8. Taken at face value these results might tend to indicate that the apparent oxygen deficiency in M 54 was due to a stellar luminosity function deficient in high-mass SN II progenitors, rather than to an above-average contribution of Fe by SNe Ia.

5. Other Evidence for Young Stars in the Galactic Halo

Perhaps the most unambiguous evidence for the existence of massive stars in the Galactic halo is provided by the observation (van den Bergh & Kamper 1977) that the progenitor of Kepler’s supernova of 1604 had a very high space velocity. Adopting a conservative distance of 4.5 kpc Bandiera & van den Bergh (1991) derived a space velocity of 278 ± 12 km s⁻¹ for this remnant. Furthermore Bandiera (1987) showed that the observed velocities in, and the spatial distribution of, the nebulosity in the remnant of SN 1604 exhibit a pattern that is best reproduced by the stellar wind of a massive evolving star, that is interacting with the low-density interstellar medium in its environment. Bandiera concludes that the progenitor of Kepler’s supernova was a massive object ($M > 10 M_{\odot}$) that is currently losing mass at a rate of $\sim 5 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$. He shows that this object must have left the Galactic plane with a velocity of ~ 340 km s⁻¹ some 3×10^6 yr ago. The remnant of Kepler’s supernova is presently situated at $Z = +530$ pc. The existence of runaway OB stars, and of Kepler’s supernova, demonstrate that not all high-velocity halo objects belong to an old stellar population.

The fact that the outermost Galactic halo has a (small) retrograde velocity, in conjunction with the observation of streaming motions in the halo (Majewski, Hawley & Munn 1996, Majewski, Munn & Hawley 1996), suggests that a large fraction of the outermost halo population was accreted. Presumably the rate at which this accretion took place was initially quite high. However, some of this capture by the protoGalaxy appears to have taken place only 3–10 Gyr ago. From a survey of young blue halo stars Unavane, Wyse & Gilmore (1996) conclude that up to 10% of the Galactic halo may consist of accreted

stars. Preston, Beers & Sheckman (1994) have reviewed evidence for the presence of such young and intermediate-age stars in the Galactic halo. They conclude that blue metal-poor stars in the halo are the bluest main sequence members of a metal-poor intermediate-age population, that was probably captured in the form of dwarf spheroidal galaxies. They estimate that 4–10% of the Galactic halo consists of such intermediate-age accreted stars. The Galactic halo has $M_V = -18.4$ (Suntzeff 1992). The total luminosity of the captured material therefore has $-15.9 < M_V < -14.9$. For comparison it is noted that Sagittarius presently has a (very uncertain) luminosity of $M_V = -13.8$, i.e. the total amount of captured stellar material in the halo is probably equivalent to 3–7 Sagittarius dwarfs. (A smaller number of “Sagittarius captives” would be obtained if tidal stripping has reduced the original luminosity of Sagittarius). Since 4–5 globulars appear to be associated with Sagittarius, the corresponding number of captured globulars would be 12–35. This number is comparable to the total number of Galactic globulars with $R_{GC} > 15.0$. This shows that the entire population of globulars in the outer halo (or at least a significant fraction of it) might have been formed in dwarf spheroidals and subsequently accreted by the Galaxy. A possible argument against this view is provided by the fact that very large outer halo clusters such as Pal 4 ($R_h = 16$ pc), Pal 3 ($R_h = 17$ pc) and Pal 14 ($R_h = 24$ pc) might not have been able to survive the tidal stresses within dwarf spheroidal galaxies. Interactions between globulars within spheroidals (Rogers & Roberts 1994) might also reduce the sizes of such clusters. Shetrone, Bolton & Stetson (1998) find that some red giants in the Draco dwarf spheroidal have significantly lower values of $[Ba/Fe]$ than do field halo stars of similar $[Fe/H]$. This indicates that the dominant stellar population in the Galactic halo was probably not derived from disintegrated dwarf spheroidals.

6. Globulars as Nuclei of Dwarf Spheroidals

It has been argued (Larson 1996) that M 54 might be the nucleus of the Sagittarius system. However, van den Bergh (1986) has shown that the fraction of spheroidal galaxies that have nuclei is strongly dependent on luminosity, and ranges from 100% at $M_V = -17$, to $\sim 15\%$ at $M_V = -12$. Adopting $M_V = -13.8$ for Sagittarius, and assuming the same nuclear frequency as is found for spheroidal galaxies in the Virgo cluster, one finds that the a priori probability that Sagittarius had a nucleus is slightly less than 50%. A higher probability would, however, be obtained if the luminosity of Sagittarius has, because of tidal stripping, decreased over time. Very recently Dinescu, Girard & van Altena (1999) have noted that the orbital characteristics of ω Centauri are consistent with the hypothesis that this object was also once the nucleus of a dwarf galaxy that was subsequently destroyed by tidal forces. If this hypothesis is correct, then two of the most luminous Galactic globulars

might both have started their existence as the nuclei of dwarf galaxies. This suggests the possibility that all globular clusters started out as the cores of more extended stellar distributions. In this respect they might have resembled OB associations, which sometimes have young open clusters in their cores.

7. Associations and Giant Clusters

The 30 Doradus nebula, and its central ionizing cluster R 136, is the nearest (and best-studied) super star forming region. From UBV photometry Malamuth & Heap (1994) derived a total mass of $16\,800\,M_{\odot}$ for R 136. Neglecting mass loss by evolving stars, and assuming $M/L_V = 3$ for clusters with ages ~ 10 Gyr, yields $M_V = -4.5$ for R 136 at age 10 Gyr. This is 2.86 mag lower than the value $\langle M_V \rangle = -7.36$, that Harris (1991) finds for all Galactic globulars. The mass gap between R 136 and typical globulars would have been even greater if the mass loss by evolving stars had been taken into account. In other words, R 136 will (if it survives for 10 Gyr) be more than an order of magnitude less luminous (massive) than typical Galactic globulars. This suggests that the formation of a typical Galactic globular was probably accompanied by a much greater burst of star formation than that which is presently observed in the 30 Doradus region.

The structure of the 30 Doradus region is complex (Walborn 1991). Rubio et al. (1998) show that the central dense cluster R 136 has triggered a second generation of star formation. These authors speculate that 30 Dor will eventually become a giant H II shell resembling N 11 in the LMC and NGC 604 in M 33. This suggests that the even greater bursts of star formation, that produce typical globular clusters, will give rise to a huge “super association”. Presumably such an association of secondary stars will, over a Hubble time, be tidally stripped from globulars in the main body of the Galactic halo. However, such associations might have survived around some of the globular clusters in the outer halo of the Galaxy where tidal forces are weak. This is so because it requires many perigalactic passages to remove the bulk of the stars beyond the tidal radius. Over the lifetime of the cluster there will be a continual flow of new stars out of the cluster envelope into the extra-tidal region. Combined with the long orbital periods of objects in the outer halo this will substantially increase our chances of detecting these stars. A multi-color search for the envelopes surrounding remote globulars might profitably be undertaken with the large area detectors that have recently become available. It should, perhaps, be emphasized that most of the stars in dwarf spheroidal galaxies were probably not produced during secondary bursts of star formation that were triggered by young globular clusters. This is so because most dwarf spheroidals do not have globular clusters embedded within them.

Furthermore the globulars that are associated with the Fornax and Sagittarius systems contribute only 2.7% and 3.0%, respectively, to the integrated luminosities of their parent galaxies. (Their fractional contribution to the total mass is probably even smaller). A physical distinction between super associations triggered by formation of a young globular, and dwarf spheroidals is that associations do not contain dark matter, whereas (most?) dwarf spheroidals do (Moore 1996).

8. Conclusions

1. Many of the Galactic globular clusters with $R_{GC} > 15$ kpc might originally have formed in dwarf spheroidal galaxies. Formation of globular clusters appears to have continued for up to 7 Gyr in dSph galaxies and in the Galactic halo beyond $R_{GC} = 15$ kpc. This contrasts with the situation in the main body of the Galactic halo in which globulars have only a small age range. It is not clear why the guillotine that cut off cluster formation at $R_{GC} < 15$ kpc did not operate in the outer halo and in dwarf spheroidal galaxies.
2. In the outer halo there may be some evidence for a decline of the mean luminosity of new born globular clusters with age. A few late forming objects, like Pal 1, have characteristics that make them appear to be intermediate between open clusters and globular clusters.
3. The luminous globular clusters ω Centauri and M 54 (= NGC 6715) may once have been the nuclei of dwarf spheroidal galaxies. Since about a quarter of all presently known “young” globular clusters are located in dwarf spheroidal galaxies, it might be worthwhile to search for the remnants of faint dSph galaxies surrounding the “young” globulars in the outer halo.
4. Negative energy (stable) clusters are situated in the cores of positive energy expanding Galactic associations. Furthermore R 136 appears to have induced secondary star formation in the 30 Doradus region. This suggests that an envelope of secondary stars might have been formed around globular clusters. Galactic tidal forces will have removed such shells from globular clusters at small and intermediate galactocentric distances. However, it might still be possible to find remnants of shells of secondary star formation around some globulars with $R_{GC} > 15$ kpc.
5. Available data on the half-light radii of globular clusters suggest that the LMC and the Fornax dwarf formed separately from the Milky Way, but that the Sagittarius dwarf may have formed as part of the outer protoGalaxy.

6. Stars with large space velocities need not all be old. Kepler’s supernova is the prototype of high-velocity halo stars that were dynamically ejected into the Galactic halo. Only very high velocity binaries like HD 134439/40 or outer halo clusters, such as Rup 106 and Pal 12, are likely to provide insight into the chemical evolution of the outer Galactic halo.

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Table 1. PROPERTIES OF “YOUNG” GLOBULAR CLUSTERS^a

Name	R_{CG} (kpc)	M_V	$[\text{Fe}/\text{H}]$ (dex)	R_h (pc)	dSph
Arp 2	29	-5.3	-1.76	15.9	Sgr
Eridanus	90	-5.1	-1.46	10.5	...
Fornax No. 4	138	-7.4	-1.35	3.0	For
IC 4499	19	-7.3	-1.60	8.2	...
NGC 4590 ^b	10	-7.3	-2.06	4.5	...
Palomar 1 ^c	11	-2.5	-0.60	2.2	...
Palomar 3	93	-5.7	-1.66	17.8	...
Palomar 4	109	-6.0	-1.48	17.2	...
Palomar 12	19	-4.5	-0.94	7.1	Sgr ?
Palomar 14	74	-4.7	-1.52	24.7	...
Ruprecht 106	21	-6.4	-1.67	6.8	...
Terzan 7	23	-5.0	-0.58	6.5	Sgr

^aData mainly from 1999 update of Harris (1996).

^b= M 68. According to Richer et al. (1996) this cluster is not “young”.

^cOld open cluster? Data from Rosenberg et al. (1998c).

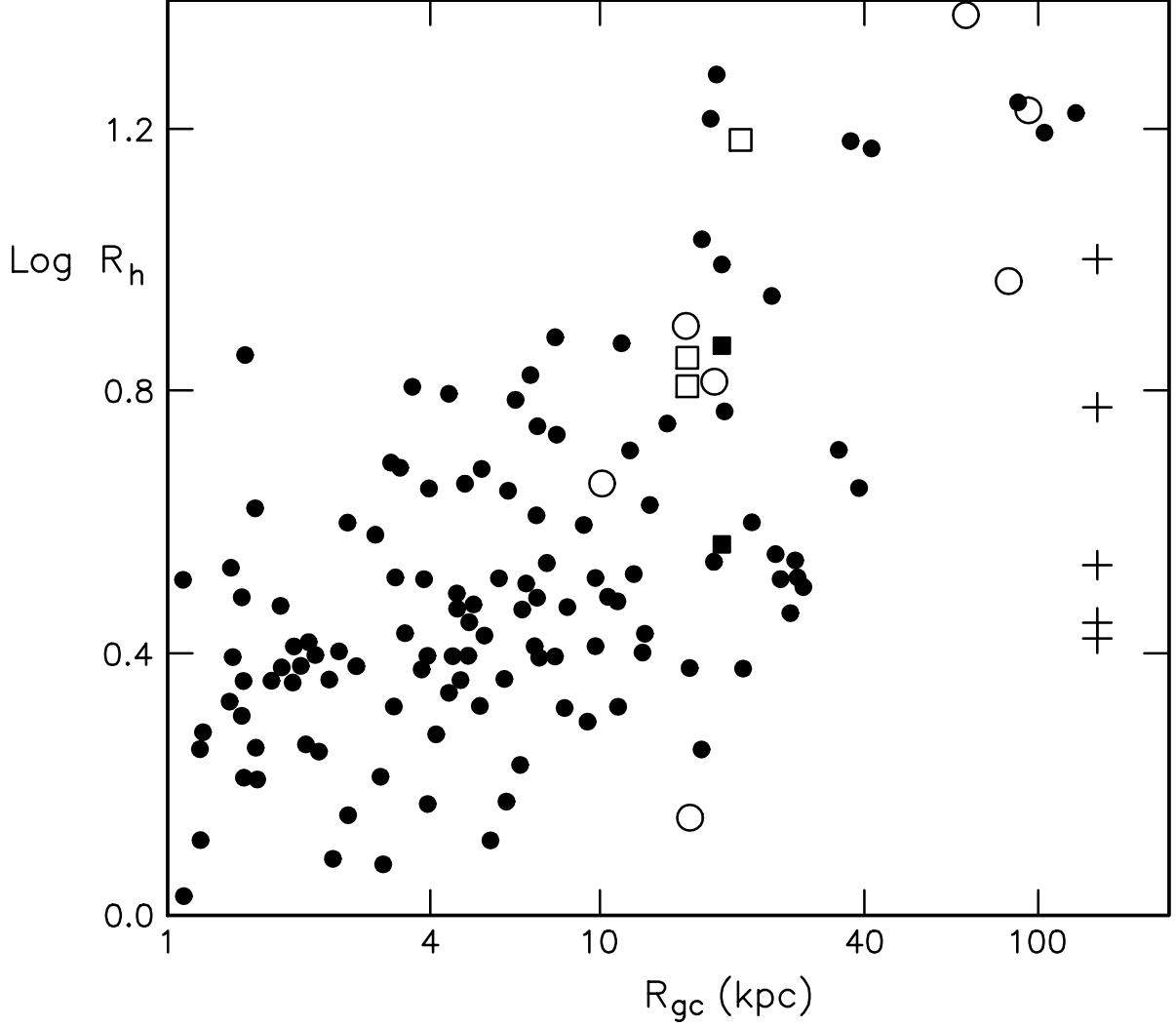


Fig. 1.— Cluster half-light radii as a function of Galactocentric distance. The Figure shows that the half-light radii of Galactic globular clusters are strongly correlated with their Galactocentric distances. No difference is seen between the positions of “young” globulars (open circles) and globulars associated with the Sagittarius dwarf (open squares), and those associated with the Galaxy (filled circles). However, clusters associated with the Fornax system (plus signs) and the LMC (not shown) have a different distribution. This suggests that the Galaxy, the LMC and Fornax were already distinct stellar systems at the time when they started to form their globular clusters.

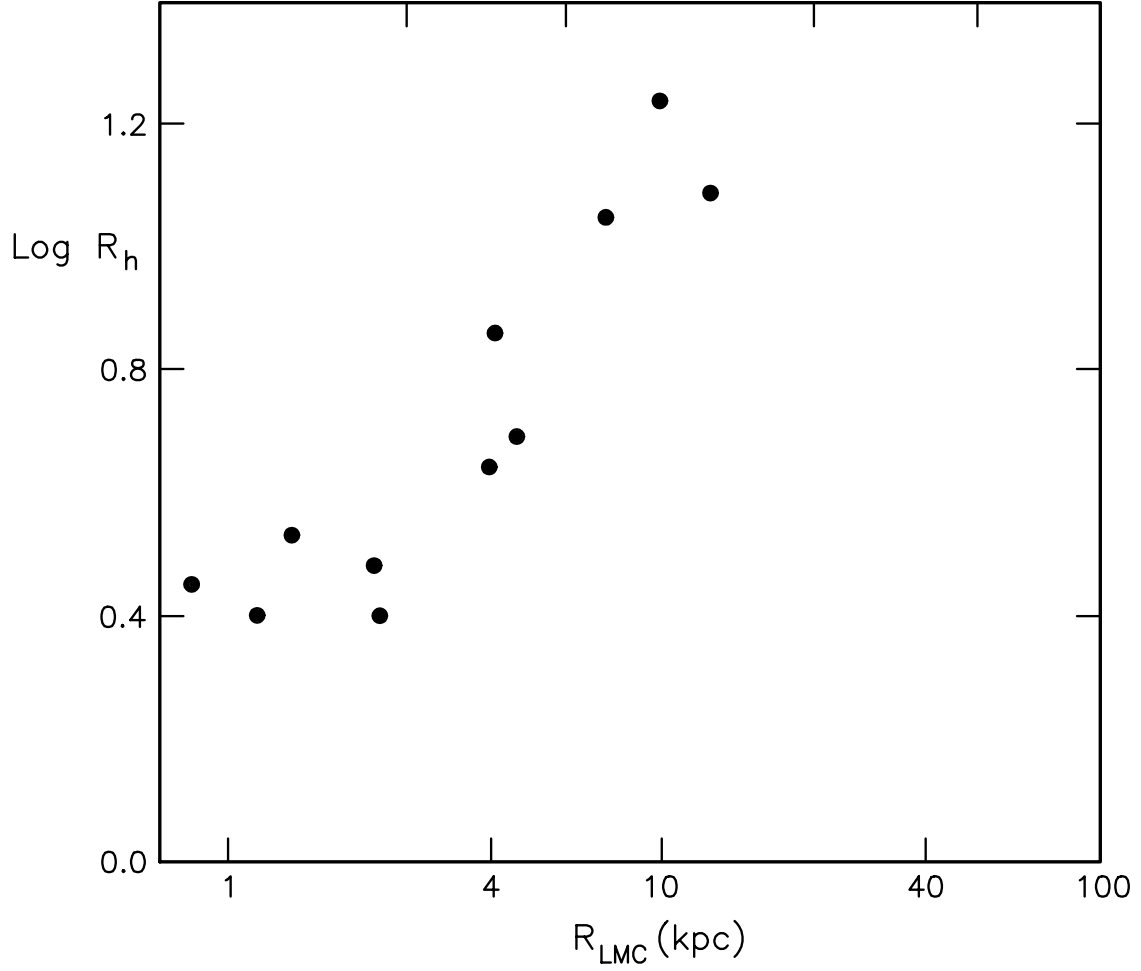


Fig. 2.— Half-light radii versus galactocentric distances for globular clusters associated with the Large Magellanic Cloud. The figure shows that R_h increases with distance from the center of the LMC. This shows that the Large Cloud cluster system formed independently from the Galactic globular cluster system. At a given galactocentric distance the Large Cloud globulars tend to be larger than their Galactic counterparts.